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A review for absorbtion and adsorbtion solar cooling systems in China

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ABSTRACT

In the past decades, solar water collectors were installed for the main purpose of preheating domestic hot water or to cover a fraction of the space heating demand in China. However, solar cooling systems were constructed just for demonstration purposes. Since the building of the first solar-powered absorption cooling system in Shenzhen in 1987, there have been over 10 additional solar cooling demonstration projects constructed. In this paper, the most representative five projects including both absorption and adsorption cooling systems are introduced and summarized. From the demonstrations, solar absorption cooling systems have been shown to be more suitable for large building air-conditioning systems. Comparatively, solar adsorption cooling systems are more promising for small size air-conditioning systems. In order to attain high utilization ratio, it is highly recommended to design solar-powered integrated energy systems in public buildings. In addition, highly efficient heat pumps are considered as the most appropriate auxiliary heat sources for solar cooling systems, for the purpose of all-weather operation. In the 11th Five year research project (duration 2006–2010), solar cooling technologies will be further investigated to achieve a breaking through in the integration of solar cooling systems with buildings.

Contents

1. Introduction

Solar cooling has been proved to be technically feasible. It is particularly an attractive application for solar energy, because of the near coincidence of peak cooling loads with the available solar power.

Solar cooling systems can be classified into three categories: (i) solar sorption cooling; (ii) solar-related systems; and (iii) solar-mechanical systems. The first two categories are based upon solar thermal utilization, whereas the third category utilizes a solar-powered prime mover to drive a conventional air-conditioning system. The solar-powered prime mover can be either a Rankine engine or an electric motor based on solar photovoltaic principle. Solar photovoltaic panels have a low field efficiency of about 10–15%, depending on the type of cells used, which results in low overall efficiencies for the system [1]. Moreover, considering an identical refrigeration output, solar-mechanical systems are four to five times

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more expensive than the solar thermal powered systems [2]. Therefore, the majority of solar-powered air-conditioning systems at present are solar sorption and solar-related systems based on solar thermal utilization. According to the main results of the EU project SACE (Solar Air Conditioning in Europe), Constantinos et al. concluded that solar air conditioning had a strong potential for significant primary energy savings. In particular, for southern European and Mediterranean areas, solar-assisted cooling systems could lead to primary energy savings in the range of 40–50%. Related cost of saved primary energy lay at about 0.07€/kW h for the most promising conditions [3].

Currently, most of the solar cooling systems commonly used are the hot water driven lithium bromide absorption chillers. Several researches including both simulation analyses and experimental investigations have been reported. With respect to simulation analysis, TRANSYS program has been widely used to analyze solar absorption cooling systems. Florides et al. modeled a solar-powered absorption cooling system of a typical house in Cyprus using TRNSYS simulation program and the weather conditions of Nicosia, Cyprus. The final optimum system consisted of a 15 m^2 compound parabolic collector tilted at 30° from the horizontal and a 600 l hot water storage tank [4]. Balghouthi et al. carried out a simulation using TRANSYS program in order to select and size different components of solar-powered absorption cooling systems. The simulation results showed that solar-powered absorption cooling systems were suitable for Tunisian's conditions [5]. Assilzadeh et al. presented a solar cooling system that had been designed for Malaysia and similar tropical regions using evacuated tube solar collectors and LiBr absorption unit. The modeling and simulation of the solar absorption cooling system was carried out using TRANSYS program. The typical meteorological year file containing the weather parameters for Malaysia was used to simulate the system. The results showed that a 0.8 m^3 hot water storage tank was essential in order to achieve continuous operation and increase the reliability of the system. The optimum system for Malaysia's climate for a 3.5 kW system consisted of 35 m^2 evacuated tube solar collectors tilted at 20° [6]. Xavier García Casals performed a detailed dynamical simulation using TRANSYS of some of the first commercial solar heating and cooling installations implemented in Spain, and analyzed their perspectives in comparison with other solar cooling options [7].

In addition to TRANSYS analysis, Atmaca et al. developed a computer program for a solar absorption cooling system to simulate various cycle configurations and solar energy parameters for Antalya, Turkey. The effects of hot water inlet temperatures on the coefficient of performance and the surface area of the absorption cooling components were studied. For this study, an 80 °C reference temperature which was the minimum allowable hot water inlet temperature was the best choice [8]. Li et al. theoretically analyzed temperature stratification in the thermal storage tank. The calculation results showed that, the solar absorption cooling system operating in partitioned mode could provide cooling effect much earlier compared to conventional whole-tank designs, and achieved a higher COP [9].

As for experimental investigations, Li et al. reported on the performance of a solar powered absorption cooling system with a partitioned hot water storage tank. The system employed a flat-plate collector array with a surface area of 38 m^2 to drive a LiBr–H_2O absorption chiller of 4.7 kW cooling capacity. The system could attain a total solar cooling COP of about 0.07 [10]. Syed et al. reported some novel experimental results derived through field testing of a part load solar energized cooling system for typical Spanish house in Madrid during the summer period of 2003. Solar hot water was supplied by a 49.9 m^2 array of flat-plate collectors, and used to drive a single-effect (LiBr/H_2O) absorption chiller of 35 kW nominal cooling capacity. A minimum hot water inlet temperature to the generator of 65 °C was required to commence cold generation. The measured maximum instantaneous, daily average and period average COP were 0.60 (at maximum capacity), 0.42 and 0.34, respectively [11].

Another potential solar-powered cooling system is the solar adsorption cooling system. The main difference compared to the absorption systems is that two or more adsorbers are necessary in order to provide continuous operation. Adsorption systems allow for somewhat lower driving temperatures but have a somewhat lower COP compared to absorption systems under the same conditions. The use of adsorption cooling technology is preferable for minitype solar-powered cooling systems [3,12,13].

Khattab developed a mathematical model to simulate and optimize the performance of a solar-powered adsorption refrigeration module with the solid adsorption pair of charcoal and methanol [14]. Saha et al. analyzed a dual-mode silica gel–water adsorption chiller which utilized effectively low-temperature solar or waste heat sources of temperature between 40 and 95 °C. Two operation modes were possible for the advanced chiller. The first operation mode worked as a highly efficient conventional chiller where the driving source temperature was between 60 and 95 °C. The second operation mode worked as an advanced three-stage adsorption chiller where the available driving source temperature was very low (between 40 and 60 °C). Simulation results showed that the optimum COP values were obtained at driving source temperatures between 50 and 55 °C in three-stage mode, and between 80 and 85 °C in single-stage, multi-bed mode [15]. Li et al. established a lumped parameter model to investigate the performance of a solar-powered adsorption air-conditioning system driven by flat-type solar collectors. One of the major contributions of the model was its simplicity and convenience in analyzing the performance of such hybrid systems. The proposed model could predict well the dynamic response of adsorption systems for given operational conditions [16].

Up to now, experimental studies on solar-powered adsorption cooling systems were mainly based on performance of adsorption chillers. Saha et al. experimentally investigated a double-stage, four-bed, non-regenerative adsorption chiller powered by solar/waste heat sources between 50 and 70 °C. The prototype studied produced chilled water at 10 °C and had a cooling power of 3.2 kW with a COP of 0.36, when the heating source and heat sink temperatures were 55 and 30 °C, respectively. Flat-plate solar collectors could easily produce hot water to regenerate the adsorbent of the chiller at this level of temperature [17]. Liu et al. developed an adsorption chiller with the working pair silica gel–water that had no refrigerant valves. This feature reduced the cost of the chiller, and made it more reliable, as there were fewer moving parts, which could allow air infiltration. The sorption bed of such a chiller could be regenerated by hot water of between 75 and 90 °C. The whole chiller contained 52.8 kg of silica gel divided between two adsorbent beds, which operated out of phase and thus, produced continuous cooling. Experiments with the first prototype showed that a cooling power of 3.56 kW and a COP of 0.26 could be obtained when the mass and heat recovery processes were employed under the follow operation conditions: evaporation temperature of 7 °C, heat sink temperature of 28 °C, and heat source temperature of 85 °C. The chiller was especially suitable for solar cooling systems with evacuated tube solar collectors as the source of thermal energy [18].

Today about 70 solar cooling systems are installed in Europe, which underlines the fact that solar cooling technology is still in an early stage of development. Most of the systems were realized in either Germany or Spain. The cooling capacity of all the installed systems sums up to about 6.3 MW and the total solar collector area

to about 17,500 m^2. It is counted that about 59% of systems are solar absorption cooling systems, and about 11% of the installations are solar adsorption cooling systems. See Henning [19] for a detailed account of the solar cooling systems in Europe.

Solar energy is abundant and clean. More than two-thirds of areas in China receive annual total radiation above 6000 MJ/m^2 with more than 2200 h of sunshine. This may be sufficient to substitute conventional energy sources. Solar energy therefore has an important role to play in the building energy system. Since 1980, solar water collectors have undergone a rapid development with an annual average growth of 30%. By the end of 2006, a total of over 90,000,000 m^2 solar water collectors have been put into use nationwide. They were installed for the main purpose of preheating domestic hot water and/or to cover a fraction of the space heating demand. However, solar cooling systems were constructed just for demonstration projects. Since the installation of the first solar-powered absorption cooling system in Shenzhen in 1987, there have been over 10 solar cooling demonstration projects put into service. This paper presents a short overview on the development of solar cooling systems in China. The most representative five projects including both absorption and adsorption cooling systems are introduced and summarized, and finally some suggestions are given.

2. Demonstration projects based on solar-powered absorption cooling system

2.1. Demonstration projects in Shenzhen

In 1987, a solar-powered cooling and hot water system was designed, constructed and was set in operation in Shenzhen, Gaungdong Province (longitude 113.17°E, latitude 22.23°N) [20]. The system provided cooling in summer to guestrooms with a total area of 80 m^2, and supplied hot water to the hotel in other seasons. The system consisted of the following main components:

1. Solar collector system with three types of solar collectors:
   (a) Pass-through type evacuated tube collector (glass-to-metal sealed), aperture area 38 m^2.
   (b) Heat pipe vacuum tube collector (glass-to-metal sealed), 38 m^2.
   (c) Flat-plate collectors with V-corrugated insulating film, 41 m^2.
2. Two sets of single-stage lithium bromide absorption chillers with a cooling capacity of 7 kW each (Japanese made, model WFC-600 Yazaki Co.).
3. Two storage tanks for hot and chilled water of volume 5 m^3 each.
4. Automatic control system: A control system was designed to decide when to start the first and second chiller depending on the stored amount of heat and the trend of solar radiation, so that frequent switching on and off of the chillers, could be avoided.
5. An automatic hot-water boiler was used as the auxiliary heat source.

As the first solar cooling demonstration project in China, the implementation of this project demonstrated technical successes and feasibility of solar cooling application in South China. The chillers worked well within their specified limits of operation. On clear sunny days, the solar-powered system could provide cooling for guestrooms during the day as well as night-time, early morning excepted. However, there existed two main disadvantages which baffled the widespread practical use of such technology. One main problem was the economical aspect, as it required costly high-grade solar collectors to provide a generation temperature of about 90 °C in order to satisfy the strict driving temperature demand of the chiller. The other problem was that the chiller could not always operate at its nominal rating during periods of low solar radiation and high cooling water temperature because the temperature in the storage tank could not always be maintained at a temperature as high as 88–90 °C throughout the day even on clear sunny days [20].

Since then, a lot of researches have been carried out to develop new-type absorption chillers which are more suitable for solar cooling systems. A significant progress was achieved with the successful operation of a 70 kW (rated cooling capacity) two-stage absorption chiller in Guangzhou Iron & Steel Plant in 1994. This chiller could operate smoothly with a heat source temperature ranging from 65 to 85 °C. According to the test results, when the hot water temperature was 80 °C, the cooling capacity attained was 79.2 kW with a thermal COP of 0.39. Even when the hot water temperature was as low as 66 °C, such chiller still operated stably and produced chilled water with the temperature of 9 °C [21]. Since then, locally fabricated absorption chillers have been manufactured and used in solar cooling systems.

2.2. Demonstration projects in the 9th Five year research project (duration 1995–2000)

During the 9th Five year research project (duration 1995–2000), two large-scale demonstration projects of solar absorption cooling systems were built in Jiangmen (longitude 113°E, latitude 22.40°N) and Rushan (longitude 121.1°E, latitude 36.40°), respectively [20,22,23]. The main characteristics of the two systems are listed in Table 1.

The building in Jiangmen was a 24-storey building, which consisted of hotels, business centers, entertainment places and an education center. A solar system was installed on the roof of the building. It supplied hot water to the building for daily use throughout the year and provided air conditioning for the education center, which was located on the 22nd floor. The schematic diagram of the cooling system is shown in Fig. 1.

In this system, conventional flat-plate solar collectors were modified by adding a thin transparent sheet between the absorber plate and the glass cover to suppress the convective heat loss from the top, thus improving the performance of the collector when operating at higher temperatures. Experimental results showed that the thermal performance of this type of solar collectors was

Table 1
Main characteristics of the systems in Jiangmen and Rushan.

Components	Jiangmen project	Rushan project
Type of solar collector	Modified flat-plate collector	Heat pipe evacuated tubular collector
Solar collector area	500 m^2	540 m^2
Type of chiller	Two-stage LiBr absorption chiller	Single-effect LiBr absorption chiller
Nominal cooling capacity	100 kW	100 kW
Hot water temperature	75 °C	88 °C
Chilled water temperature	9 °C	8 °C
Air conditioned area	600 m^2	1000 m^2
Auxiliary heat source	Oil boiler	Oil boiler

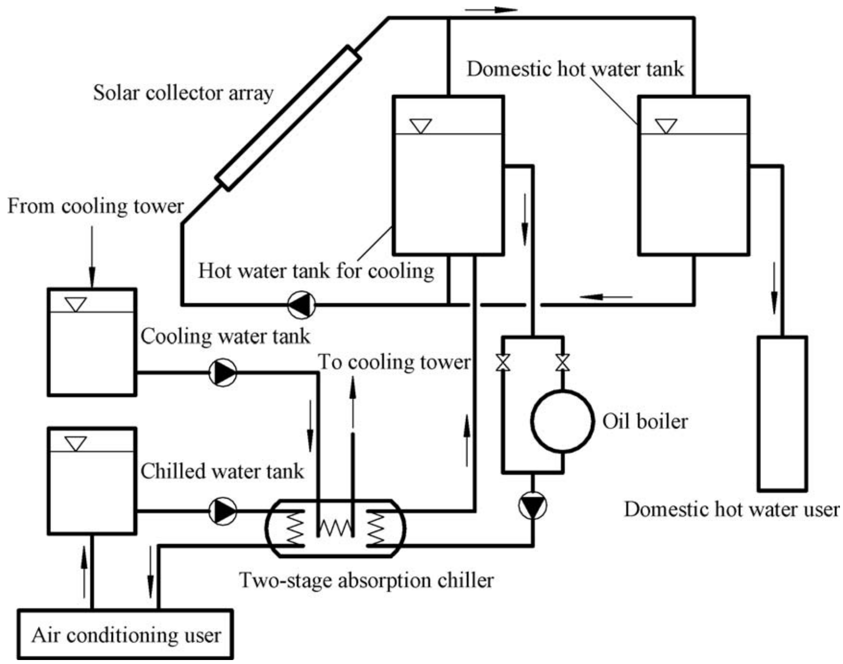

Fig. 1. Schematic of integrated solar cooling and hot water system in Jiangmen.

satisfactory. They were capable of continuously supplying hot water for cooling with sufficient solar insolation. Even when solar insolation was not enough, they could produce adequate domestic hot water.

The two-stage LiBr absorption chiller for this project could operate well with hot water temperature between 65 and 75 °C with satisfactory cooling capacity, and could assure a steady performance when the hot water temperature was as low as 60 °C. Besides, unlike a single stage chiller, where its usable temperature drop was only 6–8 °C, the two-stage chiller had a usable temperature drop of about 12–17 °C. This means, the two-stage chiller could adapt to a wide temperature range, and could extract more of the heat from the given heat source, thereby producing a higher cooling effect. It was seen from the experimental results that the chiller gave satisfactory cooling capacities as well as expected COP values. It is worth noting that the chilled water temperature could reach 7 °C when the hot water temperature was 62 °C. The thermal COP of the chiller remained the same at a value of about 0.4 even when the generator temperature varied over a wide range [20].

Fig. 2 shows the system schematic of Rushan project. In this system, heat pipe evacuated tubular solar collectors were adopted, which were capable of supplying hot water at 90 °C or more for the LiBr absorption chiller. The solar collectors were divided into nine rows and integrated with the building roof at an angle of 35° to the ground surface which is close to the local latitude. Two heat storage water tanks with the volume of 8 and 4 m^3, respectively, were adopted. The bigger one was used mainly for accumulating superfluous heat. However, the smaller one was installed to guarantee quick start of the solar cooling system. Experimental results showed that the water temperature inside the smaller tank could reach 88 °C before 9:30, which satisfied the requirement of solar cooling system. It was concluded that the system operating in such mode could realize the solar cooling effect nearly 1.5 h earlier than that only with a big tank mode. Moreover, the structures of the two heat storage water tanks were specially designed in order

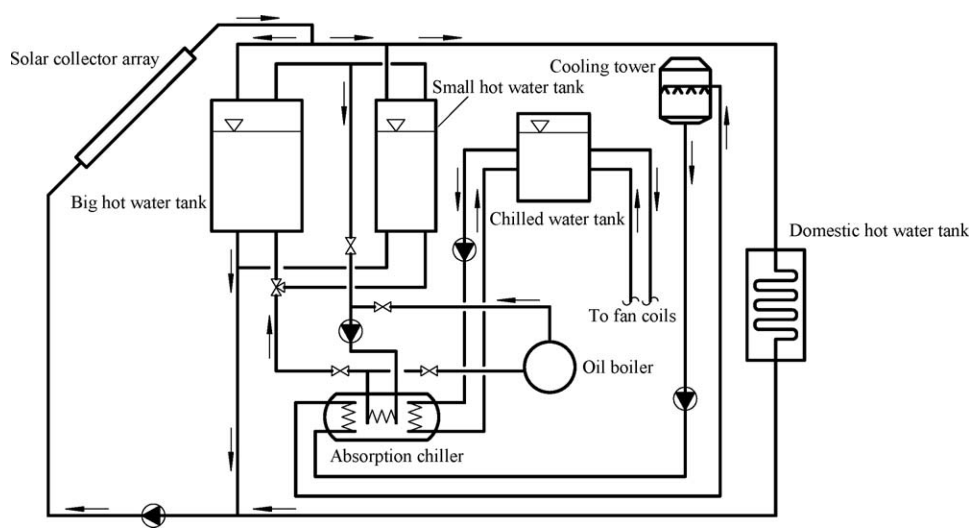

Fig. 2. Schematic of integrated solar cooling and hot water system in Rushan.

Table 2
Main characteristics of the systems in Tianpu and Beiyuan.

Components	Tianpu project	Beiyuan project
Type of solar collector	Heat pipe evacuated tubular solar collectors and U-type evacuated tubular solar collectors	Heat pipe evacuated tubular collector
Solar collector area	812 m^2	655 m^2
Type of chiller	Single-stage LiBr absorption chiller	Single-effect LiBr absorption chiller
Nominal cooling capacity	200 kW	360 kW
Hot water temperature	75–90 °C	83–88 °C
Chilled water temperature	12–15 °C	8–11 °C
Air conditioned area	8000 m^2	3000 m^2
Auxiliary heat source	Ground-source heat pump	Electric boiler

to attain thermal stratification. Generally, the temperature difference between the upper part and the bottom part of the heat storage water tanks could reach 8–10 °C.

Another characteristic of Rushan project was that a chilled water storage tank with the volume of 6 m^3 was installed. Consequently, superfluous energy could also be stored by means of chilled water. Compared with heat storage mode, such chilled water storage mode has the advantage of lower thermal loss because of lower temperature difference between chilled water and the ambient. It was reported that the daily solar collecting efficiency of the solar collector system was 40% in summer. The cooling capacity of this system was about 100 kW, with the average cooling COP of 0.57 during 6 h effective operation. The solar COP reached 0.2 [23].

2.3. Demonstration projects in the 10th Five year research project (duration 2001–2005)

During the 10th Five year research project (duration 2001–2005), two most famous solar absorption cooling systems of Tianpu and Beiyuan were all built in Beijing (longitude 116.3°E, latitude 39.8°), which contributes greatly to the concept of green Olympics of 2008. The main characteristics of the two systems are listed in Table 2.

The Tianpu demonstration project consists of a 200 kW solar absorption cooling system assisted by a ground-source heat pump with a rated cooling capacity of 391 kW [24]. The schematic diagram of the project is shown in Fig. 3. Two kinds of solar collector modules were prefabricated: U-type solar collector module and heat pipe solar collector module. The U-type module had an area of 4.8 m^2 (4000 mm × 1200 mm) and was composed of 32 evacuated tubes with the dimension of ø58 mm × 1800 mm. The heat pipe solar collector module had the same area (2000 mm × 2400 mm), and also consisted of 32 evacuated tubes with the dimension of ø58 mm × 1800 mm. The whole solar collector array with the area of 812 m^2 included 140 U-type solar collector modules and 29 heat pipe solar collector modules, facing the south and tilted at an angle of 38 °C to the ground surface. The solar absorption cooling system could work under a driving source ranging from 65 to 95 °C. Chilled water produced by the solar cooling system was stored in a chilled water storage tank with a volume of 1200 m^3. This big water tank was installed underground for the purpose of reducing thermal loss. Besides, it was capable of realizing seasonal energy storage and the chilled water produced in spring could be stored for later use in summer. In order to maintain the setting temperature inside the cold storage water tank, the ground-source heat pump was turned on either when the water temperature was higher than 18 °C or during the period from 22:00 to 7:00 with cheaper electricity tariff. Air-conditioning inside the building was realized by means of radiant cooling system. Under design condition, the inlet and outlet temperature of chilled water was 25 and 20 °C, respectively.

Table 3 shows some performance parameters of the solar cooling system in 25th August 2003. A cooling output of 266 kW could be attained, with a corresponding thermal COP of 0.8. The solar COP was 0.2–0.3. In addition, the absorption chiller had a usable hot water temperature drop of about 14–23 °C. Such phenomenon was helpful in improving the solar collector performance because the inlet temperature of solar collectors could be decreased. It was reported that the average solar collecting efficiency in summer exceeded 40% [24].

So far the largest solar cooling system in China is the demonstration project of Beiyuan, which was constructed in 2005 [25]. The schematic diagram for this project is shown in Fig. 4. In this system, heat pipe evacuated tubular solar collectors with a total area of 655 m^2 were installed on the building roof. As the driving source of the solar cooling system, this type of collector has a high thermal efficiency, and can work efficiently under high

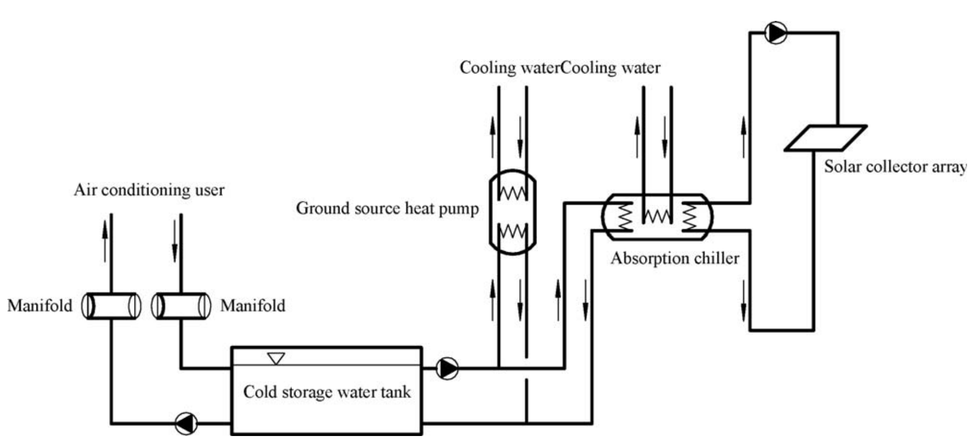

Fig. 3. Schematic plan of solar cooling system in Tianpu.

Table 3
Performance parameters of the solar cooling system in Tianpu project.

Time	Hot water temperature (°C)		Cooling water temperature (°C)		Chilled water temperature (°C)		COP	Cooling capacity (kW)
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet		
11:23	71.8	48.6	25.1	30.0	24.7	21.0	0.735	259
11:30	71.3	48.8	25.3	30.2	24.7	20.9	0.780	266
11:39	69.6	49.0	25.4	30.4	24.7	20.9	0.851	266
12:01	64.3	48.3	25.7	30.4	24.7	22.1	0.750	182
12:06	64.3	48.3	25.8	30.4	24.6	22.2	0.692	168
12:10	61.8	47.7	26.6	30.8	24.5	22.0	0.818	175
12:19	61.6	47.7	26.7	30.9	24.5	22.2	0.764	161

operation temperature (the operation temperature in summer is 80–95 °C). A single-effect LiBr absorption chiller was chosen to supply cooling to the building with an area of 3000 m^2. The rated cooling capacity was 360 kW with COP of 0.7, when the hot water temperature was between 83 and 88 °C. An electric boiler was installed as an auxiliary heat source, which guaranteed the hot water temperature requirement for highly efficient operation of the chiller. A heat storage water tank of 40 m^3 was employed to store hot water from the solar collectors and the electric boiler. Another water tank of 30 m^3 was adopted to store chilled water produced by the solar cooling system. Such design was advantageous for superfluous energy storage and stable operation of the system.

During the experimental period when the ambient temperature was about 30.3 °C, the average solar collecting efficiency and the COP of the chiller was 0.42 and 0.75, respectively. Whereas, the average indoor air temperature was 23.8 °C.

3. Demonstration projects based on solar-powered adsorption cooling systems

The most successful demonstration project based on solar-powered adsorption cooling system was implemented in the green building of the Shanghai Research Institute of Building Science (longitude 121.3°E, latitude 31.1°N). Designed to be a demonstration project, the green building contains multiple renewable energy technologies, such as solar thermal technology, solar photovoltaic, natural ventilation, natural lighting, indoor virescence, etc. The solar energy used to drive the adsorption chillers was collected by 90 m^2 of U-type evacuated tubular solar collectors with CPC installed in the southwest side of the roof, and by 60 m^2 of heat pipe evacuated tubular solar collectors installed in the southeast side. In order to enhance the efficient utilization of solar energy, the roof was tilted at an angle of 40° to the ground surface. All the solar collectors in both sides were divided into three parallel rows. The collector units in each row were connected in a serial arrangement for the purpose of achieving hot water with a relatively high temperature, which is important for improving the performance of the system. Such an arrangement of the solar collectors not only guarantees high system performance but also improves the beauty of the building facade. Furthermore, it demonstrates the feasibility of integrating solar collectors on buildings, especially the public ones.

The solar cooling system was designed and set up to operate in a building area of 460 m^2. In summer, the cooling system should meet a cooling demand of 60 kW, where 15 kW was related to the sensible cooling load, which was met by the solar-powered adsorption air-conditioner discussed in this paper. The other 45 kW relating to the latent cooling load was met by a liquid-desiccant system, which was constructed jointly by Tsinghua University and Shanghai Research Institute of Building Science. Therefore, the hybrid air-conditioning system could handle the cooling and humidity loads independently, and the fan coils inside air-conditioning rooms realize dry operating mode without condensation of vapor.

Apart from the solar collector arrays, the solar-powered air-conditioning system was mainly composed of two adsorption chillers with a nominal refrigeration capacity of 8.5 kW (when the hot water temperature is 85 °C), a cooling tower, fan coils (in the air-conditioned rooms) and water circulating pumps for the solar collectors (Pump 1), hot water (Pump 2), cooling water (Pump 3) and chilled water (Pump 4). Moreover, a heat storage water tank of 2.5 m^3 was employed to store the solar heat, and provide hot water to the air-conditioning system. All the components were connected by tubes and valves to form a whole flow circuit, as shown in Fig. 5.

Under typical summer working conditions, the daily average solar collecting efficiency was up to 39.7%. During the operation

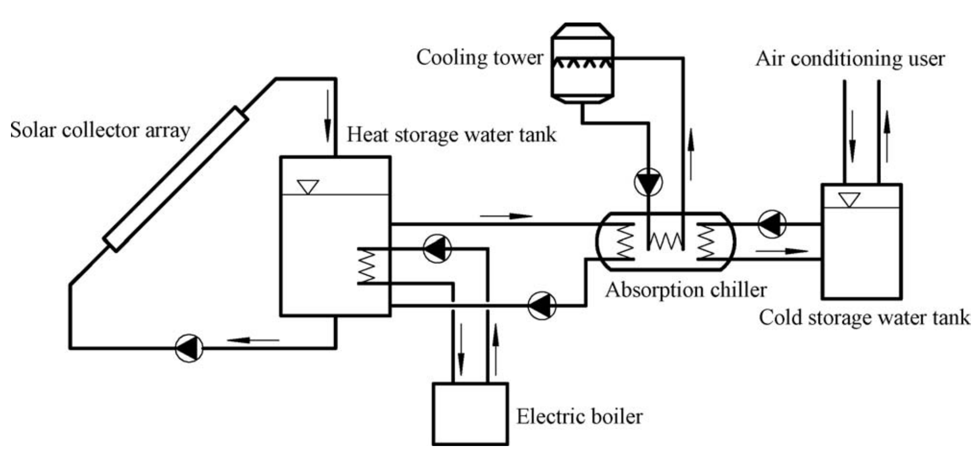

Fig. 4. Schematic plan of solar cooling system in Beiyuan.

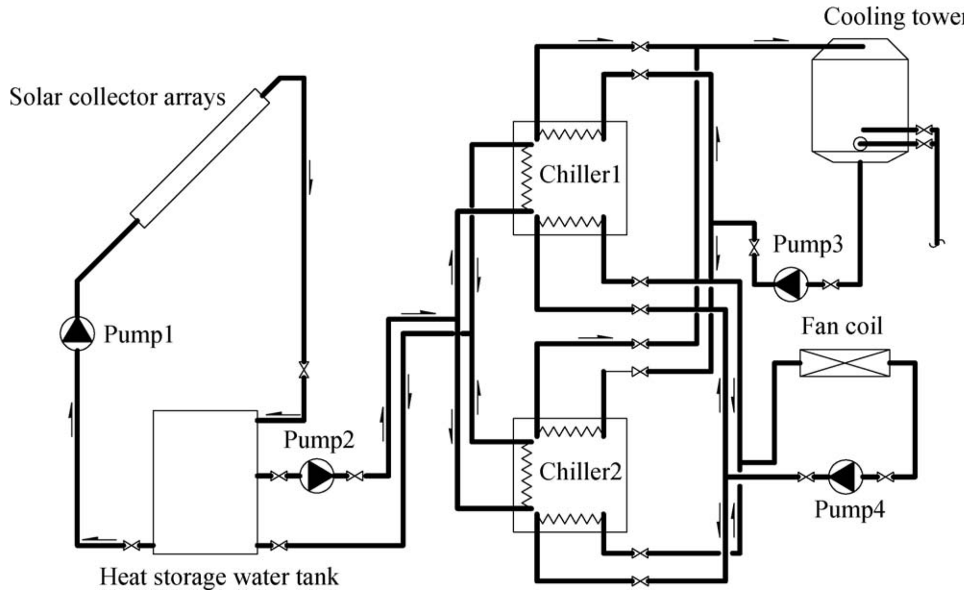

Fig. 5. Flow diagram of solar-powered adsorption cooling system.

from 9:00 to 17:00, the average hot water temperature was 70.2 °C, the system yielded an average refrigeration capacity of 15.3 kW. With regard to the heat consumption of the two adsorption chillers, the average system COP was 0.35, whereas the average solar COP was 0.15. Moreover, the maximal refrigeration capacity exceeded 20 kW. It was reported that the solar fraction for the system in summer was 72% [26].

4. Conclusions and suggestions

The main performance indexes of the most famous five demonstration projects in China (Jiangmen, Rushan, Tianpu, Beiyuan and Shanghai) in China are summarized in Table 4. During the last 20 years, solar cooling demonstration projects based either on absorption or adsorption were mainly applied in public buildings. Besides, nearly all solar cooling systems are multifunctional and were used to supply heating and hot water in other seasons.

Because of high initial cost and high specific collector area (the installed solar collector area per unit of installed cooling capacity); solar cooling technologies are still unsuitable to be spread on a large scale in residential buildings. As for public buildings, it is highly recommended to design solar-powered integrated energy systems. Owing to the fact that there are always enough roof area to install solar collectors, solar-powered integrated energy systems are capable of supplying cooling and heating, and even can enhance natural ventilation besides hot water supply [26]. Such designs have the advantages of high utilization ratio, strong adaptability to seasons, and thus high solar fraction, which makes the solar-powered integrated energy systems more economical.

Solar energy systems used only for cooling purposes, are not economically viable and the capital cost are very high. The initial cost of solar collectors accounts for 60–70% of the total invest of solar cooling systems. Consequently, solar cooling systems must be implemented along with hot-water supply. For example, for the solar-powered integrated energy system in the green building of Shanghai Research Institute of Building Science, the pay back period is about 2–3 years if hot water is utilized for bathing or showering, however, the pay back period could be 7–8 years if the hot water is only used for space heating and cooling for the building.

Currently, the main approaches used to improve performance of solar cooling system include improvements of both chillers and solar collectors. On one hand, new type thermally driven chillers with low driving temperature are being developed. Whereas, on the other hand, moderate and high temperature solar collectors which are capable of supplying high temperature heat source are being studied. The former is more meaningful and adaptive for China due to the fact that nearly all solar collectors on the market are ordinary flat-plate or evacuated tubular solar collectors. As a result, emphasis has been put to develop thermally driven chillers which can be matched with solar collectors available on the market. At present, there are two main research aspects involving lithium bromide absorption chillers and silica-gel adsorption chillers. From the demonstration projects, it was observed that the capacity of solar absorption cooling systems has become larger and larger. They are more suitable for large building air-conditioning systems. Absorption chillers are available from various manufactures, in large capacities up to several thousand kilowatts.

Table 4
Performance parameters of five most famous demonstration projects in China.

	Jiangmen	Rushan	Tianpu	Beiyuan	Shanghai
Solar collector type	Flat-plate		Evacuated tubular		
Solar collector efficiency	0.45	0.40	0.40	0.42	0.40
Chiller type	Absorption	Absorption	Absorption	Absorption	Adsorption
Driving temperature	75 °C	88 °C	75–90 °C	83–88 °C	60–95 °C
Chiller COP	0.45	0.57	0.8	0.75	0.35
Solar COP	0.25	0.20	0.2–0.3	0.25	0.15

Table 5
Summary of solar-powered absorption cooling systems [21].

Heat source temperature (°C)	Daily average solar collecting efficiency (%)	Chiller COP	Solar COP	Chiller type	Collector type
130~	~35	~1.0	~0.35	Steam-driven double-effect	Light gathering collector
85–90	~45	~0.7	~0.315	Water-driven single-stage	Evacuated tubular collector
65–75	~55	~0.45	~0.25	Water-driven double-stage	Evacuated tubular or flat-plate collector

However, in the range of small capacities (<100 kW) only very few systems are available in the market. The application of solar-powered absorption cooling systems can be summarized as shown in Table 5 [21].

With respect to small capacity chillers, solar adsorption cooling systems are thought to be more promising in minitype building air-conditioning systems. As for working pairs, a silica gel/water adsorber can work with a waste heat source below 100 °C, which can be supplied by a wider range of solar thermal collectors. An adsorption chiller with rated cooling capacity of 10 kW, which can be powered by low-temperature solar collectors has been successfully developed by Shanghai Jiao Tong University. It is capable of working with hot water at 60–95 °C. The performance test shows that the chiller attains the rated refrigerating capacity of 10 kW when the hot water temperature is 85 °C, and the corresponding COP obtained is 0.4. Nowadays, it has been put into practice in several projects.

Most solar-powered absorption cooling projects to-date have utilized single-effect systems with low-temperature solar collectors. Development in gas-fired absorption systems in recent years, for LiBr–water chillers, have made available in the market double-effect systems with COP 1.1–1.2. These systems may be adapted to and employed in a solar-powered installation with high-temperature solar collectors. In China, such systems have been developed by Broad Air Conditioning Company. The combination of parabolic solar collectors with double-effect absorption chillers doubles the efficiency of conventional applications. This system was designed to use solar energy during day time and use an alternate fuel (natural gas) on cloudy days or at night operation, which realizes all-weather operation. Applying such air-conditioning system in the right location will yield a payback of about 3–6 years [27].

With regard to terminal equipments of solar-powered cooling systems, it is believed that the high inertia air conditioning distribution systems like radiant ceilings or walls are more suitable for solar cooling systems. Compared with fan coil air-conditioning systems, radiant cooling systems require a higher chilled water temperature of about 18–20 °C. This means that the evaporating temperature of the chillers rises about 10 °C, which leads to the increase of COP of chillers. Besides, radiant ceilings or walls are capable of regularizing the cooling load imposed on the solar absorption or adsorption systems.

For the purpose of all-weather operation, it is necessary to install auxiliary heat sources to supplement solar-powered cooling systems. From demonstration projects, it is considered that highly efficient heat pumps, either ground-source or air-source equipments depending on the given conditions, are perfect schemes to act as auxiliary heat sources. In China, it is thought that ground-source heat pumps are suitable for North China areas; however, air-source heat pumps are fit for South China areas.

5. Prospects

To some extend, the above demonstration projects have greatly promoted research and spread of solar cooling technologies in China. However, in the past decades, solar cooling systems were constructed just for demonstration purposes. In the 11th Five year research project (duration 2006–2010), with the implement of "Renewable Energy Law of China" which was implemented in 1st January of 2006, enough emphasis has been put by all provincial governments. The governments will enhance solar energy research for the purpose of achieving a breaking through in the integration of solar thermal systems with buildings.

As for integrated approach, solar collector modules integrated into building facades will be emphasized and developed. The facades of buildings can be important solar collectors. When using the integrated approach, solar systems become part of the general building design. The solar collectors cannot be separate elements that are added after the building, they should at least be considered during the architectural design. They must rather replace other building elements, thereby serving dual functions and reducing total costs.

With regard to solar cooling technologies, either solar-powered absorption or solar-powered adsorption chiller design will be optimized and standardized. The cost of chillers is expected to decrease as a result of large-scale manufacture. In addition, with the further spread of solar hot water systems in residential buildings, solar cooling technologies especially mini-type residential cooling technologies will be developed.

With respect to auxiliary heat source, corresponding to different climate characteristic, solar cooling systems assisted with highly efficient heat pump devices or other renewable energy such as geothermal energy will be investigated.

Concerning related regulations, in order to standardize the design and construction of solar hot water systems, the Ministry of Construction has promulgated "Specification of Applied Technique for Solar Energy Application in Civil Buildings" and "Collective Drawings of Selection and Installation for Solar Collectors". However, analysis software along with design specifications is necessary especially for large-scale application of solar-powered integrated energy systems. Such work will be completed in the 11th Five year research project. It is reasonable to expect that solar cooling technologies will play greater role in building energy systems in the coming years.

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